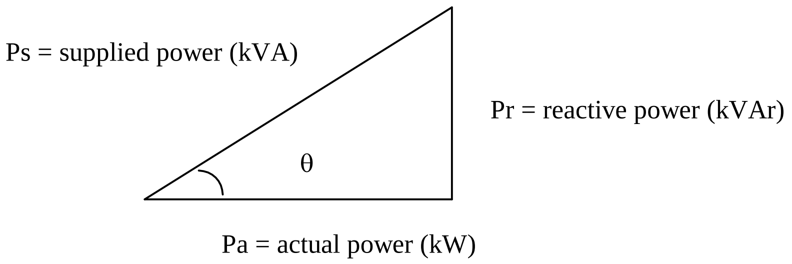
Power Factor Correction Calculations.

Resistive devices, like electric resistance heaters and incandescent lights transform all the power supplied to the device into heat or useful energy. Inductive devices, like motors, use some of the power supplied to the device to energize the inductive windings and create a magnetic field. This power, called reactive power, is alternately stored and given up by the windings, but is not used to do actual work. When this happens, the line supplying power to the device now carries the actual power used by the device and the reactive power created by the device.

Actual power used by the device is measured in kW, reactive power created by induction devices is measured in kVAr, and the apparent power in the supply lines is measured in kVA. The mathematical relationships between these types of power are described by the "power triangle" shown below. For example,

$$Ps = (Pa^2 + Pr^2)^{1/2}$$



The ratio of the actual power consumed by equipment (Pa) to the power supplied to equipment (Ps) is called the power factor.

PF = Pa / Ps = kW / kVA = cos [

Devices which generate/require large amounts of reactive power in relation to actual power consumed have low power factors. Such devices include:

- Motors
- HID and fluorescent lights with low PF ballasts

Devices which convert AC power to DC power such as:

- DC drives
- Welding machines
- VFDs
- Induction furnaces

Fully loaded motors generally have a power factor of about 80%. However, if the motor is under loaded, the fraction of reactive power (for the coil) to actual power (for mechanical work) increases and the power factor decreases.

Two potential problems are associated with low power factor. First many utilities have explicit or implicit charges for low power factor. Second, low power factor increases the current, and hence losses, in transformers and the electrical distribution system. These losses cost money and generate excess heat in the electrical distribution system, which may shorten equipment lifetime or cause production shut downs. These potential problems are discussed in the sections that follow.

Power Factor Charges:

Many utilities charge for low power. To measure power factor, the most common type of utility meter measures the total kVAr-hours and kVA-hours over the billing period and calculates the average power factor as:

PF = Cos [ArcSin (kVArh / kVAh)]

The most common methods of charging for low power factor are:

1. Adding a demand penalty when the power factor dips below a set amount (usually 90%)

For example: the Cinergy DS rate specifies a demand penalty of:

$$\text{kWactual}\left(\frac{0.9 - \text{PF}}{\text{PF}}\right) \text{ when PF} < 0.9$$

If actual power was 100 kW, the power factor was 80%, and the avoided cost of demand were $15.67 /kW, the monthly power factor charge would be:

$$100\ \text{kW}\left(\frac{0.9 - 0.8}{0.8}\right) = 12.5\ \text{kW}$$

12.5 kW x $15.67 /kW = $196

2. Basing the demand charge on the supplied power Ps (kVA), rather than the actual power used Pa (kW).

For example, assume billing demand is based on kVA rather than kW and the demand charge is $15.00 /kVA-month. If actual demand was 100 kW, the power factor was 80%, the implicit monthly power factor charge would be:

$\text{kVA}_{\text{PF = 80\%}}$ = kW / PF = 100 kW / 0.8 kW/kVA = 125 kVA
$\text{kVA}_{\text{PF = 100\%}}$ = kW / PF = 100 kW / 1.0 kW/kVA = 100 kVA
Penalty = $15 /kVA-month x ($\text{KVA}_{\text{PF = 80\%}}$ - $\text{KVA}_{\text{PF = 100\%}}$)
Penalty = $15 /kVA-month x (125 kVA – 100 kVa) = $375 /month

3. Basing part of the overall charge on the reactive power kVAr, which increases as power factor decreases.

For example, the Dayton Power and Light General Service Primary Rate specifies a charge of $0.30 per kVAr. The relationship between reactive and actual power is:

$$Pr\ (kVAr) = Pa\ (kW) \times Tan[Cos^{-1}(PF)]$$

If the actual power was 100 kW and the power factor was 80%, then the power factor charge would be:

$$Pr\ (kVAr) = 100\ (kW) \times Tan[Cos\text{-}^{1}(0.8)] = 75\ kVAr$$

$$75\ kVAr \times \$0.30\ /kVAr = \$23$$

Power Losses and Excess Heat Generation:

In addition to possible power factor charges, low power factor also results in excess current in the electrical distribution system upstream from the device. The excess line current results in increased resistive losses, and hence heat gain, in the wiring and electrical distribution equipment. The quantity of line losses associated with low power factor correction can be calculated as follows:

LL_1 = Line loss before power factor correction
LL_2 = Line loss after power factor correction
% Line Loss Savings = $(LL_1 – LL_2) / LL_1$

$$LL_1 = I^2{}_1R_1 = (kVA_1/V_1)^2 R_1 = [(kW_1/PF_1) / V_1]^2 R_1 = [kW^2 R / V^2]_1 / PF_1{}^2$$

Thus:

$$LL_2 = [kW^2 R / V^2]_2 / PF_2{}^2$$

Assuming everything remains constant except for the power factor:

$$[kW^2 R / V^2]_1 = [kW^2 R / V^2]_2 = [kW^2 R / V^2]$$

And,

% Line Loss Savings = $(LL_1 – LL_2) / LL_1$
% Line Loss Savings = $[(kW^2 R / V^2) / PF_1{}^2 – (kW^2 R / V^2) / PF_2{}^2] / (kW^2 R / V^2)_1 / PF_1{}^2$
% Line Loss Savings = $[1 / PF_1{}^2 – 1 / PF_2{}^2] / 1 / PF_1{}^2$
% Line Loss Savings = $1 – (PF_1/ PF_2)^2$

For example, if the power factor were improved from 80% to 90%, the percent line loss savings would be:

% Line Loss Savings = $1 – (PF_1/ PF_2)^2$ = $1 – (80\%/ 90\%)^2$ = 21%

In addition, the heat generation in upstream electrical distribution equipment would be reduced by 21%. This may or may not be significant. If the electrical circuits are fully loaded and tripping due to excess current, then power factor correction could mitigate this problem.

Although percent line loss savings are relatively high, total energy savings are typically small since line losses are small. For example, if line losses are 2% of the total power draw, the total power savings from correcting the power factor would be:

2% x 21% = 0.42%

Some manufactures of power factor correction equipment claim that actual losses are much greater than those calculated here, but there is little documented evidence of this in the open literature.

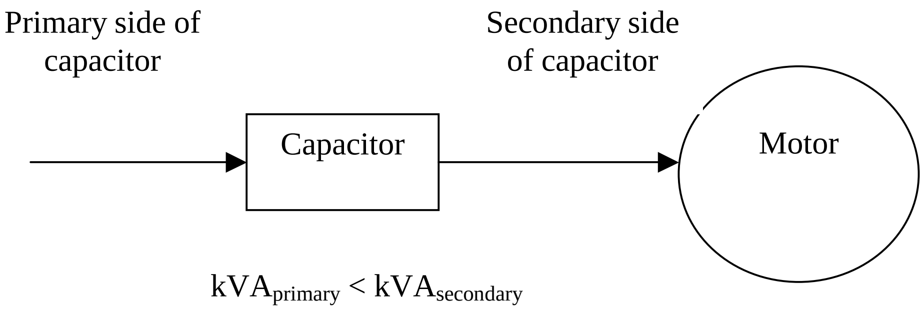
Because of these effects, it is generally in the client's interest to maintain a relatively high power factor. To maintain a high power factor:

- purchase equipment with high power factor ratings, such as high power factor lighting ballasts
- avoid or replace dramatically oversized motors, since under-loaded motors have low power factors.

If power factor is still a problem, consider adding electrical capacitors.

Sizing Capacitors and Estimating Savings:

Capacitors work by canceling reactive power and current on the primary or upstream side of the capacitor. For example, if a motor operates at 70% power factor, installing a capacitor in the power supply line to the motor would reduce reactive power and line current on the primary side of the capacitor, but would not change the line current on the secondary (motor) side of the capacitor. Thus, installing capacitors directly upstream from low-power-factor loads reduces line current throughout the plant’s electrical distribution system; whereas installing capacitors directly down-stream of the utility meter at the electrical service entrance to the plant, results in power factor correction for utility billing purposes, but will not reduce line losses and overheating throughout the plant.



$$\mathrm{kVA}_{\mathrm{primary}} < \mathrm{kVA}_{\mathrm{secondary}}$$
$$\mathrm{PF}_{\mathrm{primary}} > \mathrm{PF}_{\mathrm{secondary}}$$

The two primary types of capacitors are oil-filled and gas-filled. Oil-filled capacitors typically last about 60,000 hours and Nitrogen and helium gas-filled capacitors last about 120,000 hours. However, the substantially lower cost of oil-filled capacitors make them much more popular than gas-filled capacitors.

Capacitors are sized by the amount of reactive power (kVAr) they can cancel. Simple capacitors are sized to compensate for a fixed amount of power. "Stepped" capacitors have internal controls that adjust the amount of reactive power compensation.

Adding too much capacitance can push the system from "lagging" to "leading"; for example, adding too much capacitance may change the power factor from 95% to 105%. Although leading power factor does not harm equipment, purchasing excess capacitors is expensive and serves no useful purpose. In addition some meters may read a leading 105% power factor as 95%. If so, you would not get credit for the power factor correction from 95% to 100%. (Other utility meters would read a power factor of 105% as 100%). Because of these reasons, we recommend a conservative approach to power factor correction in which we never overcorrect the power factor past 100%.

A simple method to size the amount of capacitor kVAr required is described in the steps that follow:

1. Find kVAr for each month: Pr (kVAr) = Pa (kW) x Tan[Cos^{-1}(PF)]
2. To increase PF as close to 1.0 as possible, recommend additional capacitance equal to minimum monthly kVAr during the past 12 months. This approach minimizes the possibility of adding too much capacitance.
3. Subtract the recommended capacitance (kVAr) from recorded (kVAr) for each month. This difference represents the reactive power (kVAr) if the recommended capacitance were added.
4. Recalculate PF, kVA or kVAr and electricity costs for each month, using the reactive power calculated in the previous step. These costs represent the costs if the recommended capacitance had been added.
5. Calculate savings as the difference between the actual costs and the costs calculated in the previous step.
6. To estimate the implementation cost, we note that the installed cost of capacitors is about $20 /kVAr - $50 /kVAr, depending on control complexity and size.

Example:

According to your electricity bills, the average plant power factor is about 68%. Based on your electric rate structure, you can lower your demand charges by improving power factor. However, you do not want to over correct the power factor to more than 100%. In March 2000, power factor peaked at 74%. Thus, we recommend adding only enough capacitance to raise your power factor to 97% for that month. According to the analysis below, this would be about 400 kVAr of capacitance.

Estimated Savings:

Determining How Much Capacitance to Add:

The highest power factor registered during the period for which we were supplied with electricity data was for March 2000, when the plant power factor was 74% and the peak power was 594 kW. If the power factor during this month were corrected to 97%, the power factor during the rest of the year would never exceed 97%. Using standard trigonometric relations, the angle theta in the power triangle shown above was about:

$\text{Cos}\theta = \text{kW} / \text{kVA}$
$\theta = \text{Cos}^{-1}\ (\text{PF})$
$\theta = \text{Cos}^{-1}\ (74\%) = 42.27\ ^{\circ}$

The reactive power was about:

$\text{Tan}\theta = \text{kVAr} / \text{kW}$
$\text{kVAr} = \text{kW} \times \tan\theta$
$\text{kVAr} = 594\ \text{kW} \times \tan (42.27) = 540\ \text{kVAr}$

If the power factor were increased to 97%, the reactive power would be about:

$\text{Cos}\theta = \text{kW} / \text{kVA}$
$\theta = \text{Cos}^{-1}\ (\text{PF})$
$\theta = \text{Cos}^{-1}\ (97\%) = 14.07\ ^{\circ}$

$\text{kVAr} = \text{kW} \times \tan\theta$
$\text{kVAr} = 594\ \text{kW} \times \tan (14.07) = 149\ \text{kVAr}$

Thus, the amount of capacitance required to boost the power factor from 74% to 97% during March 2000 would be about:

540 kVAr – 149 kVAr = 391 kVAr

We recommend adding about 400 kVAr.

Calculating Savings:

According to this example electricity bills, the annual average power factor is 68% and the annual average demand is 579 kW. Using standard trigonometric relations, the angle theta in the power triangle shown above is about:

$\text{Cos}\theta = \text{kW} / \text{kVA}$
$\theta = \text{Cos}^{-1}\ (\text{PF})$
$\theta = \text{Cos}^{-1}\ (68\%) = 47.156\ ^{o}$

The reactive power is about:

$\text{Tan}\theta = \text{kVAr} / \text{kW}$
$\text{kVAr} = \text{kW} \times \tan\theta$
$\text{kVAr} = 579\ \text{kW} \times \tan(47.156) = 624\ \text{kVAr}$

If 400 kVAr of capacitance were added, the average kVAr would be about:

624 kVAr – 400 kVAr = 224 kVAr

The angle theta would be about:

$\theta = \text{Tan}^{-1}\ (\text{kVAr}/\text{kW}) = \text{Tan}^{-1}\ (224/579) = 21.150\ ^{o}$

The annual average power factor would be about:

$\text{PF} = \text{Cos}\theta = \text{Cos}\ (21.150) = 93\%$

The annual average kVA would be about:

$\text{kVA} = \text{kW} / \text{Cos}\theta = 579 / \text{Cos}(21.150\ ^{o}) = 621\ \text{kVA}$

The billing kVA would be about:

621 kVA x [1 + (0.9 - 93%)] = 602 kVA

According to this example electricity bills, the annual average power factor is 68% and the annual average kVA is 852 kVA. Thus, without power factor correction the annual average billing kVA would be about:

Actual kVA x [1 + (0.9 – PF)] = 852 kW x [1 + (0.9 – 68%)] = 1,039 kVA

Thus, the savings from correcting the average power factor to 93% would be about:

1,039 kVA – 602 kVA = 437 kVA
437 kVA x $18.08 /kVA-month x 12 months/yr = $94,812 /yr

Estimated Implementation Cost:

According to quotes from other utilities, the total installed cost for simple capacitors is no more than $20 per kVAr. If so, the total implementation cost for installing 400 kVAr of capacitors would be about:

400 kVAr x $20 /kVAr = $8,000

Estimated Simple Payback:

$8,000 / $94,812 /yr x 12 months/yr = 1 month